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Relaxation of Laser-Induced Signals from a Superconducting Tunnel Junction

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The time spectra of electric signals induced in an Sn-SnO_x-Sn superconducting tunnel junction by pulse laser light were measured under various bias conditions at low reduced temperatures. It has been revealed that the relaxation time of signals depends strongly on the bias current. As expected, the peak height is also sensitive to the bias setting. The observed time spectra as well as some discussion on the results are given.

KEY WORDS: Superconductivity/ Tunnel Junction/ Pulse Laser/

I. INTRODUCTION

There have been many works on the transient behavior of superconductors against nuclear radiations and other sources. One of the principal motivations of these studies comes from the possible use of superconductors for a nuclear radiation detector,[1-4] and the other is to examine the fundamental characteristics of non-equilibrium state.[5-11]

In a series of studies on the transient response of superconductors we observed the pulse height distribution of electric signals generated in a crossed-film Sn tunnel junction by 5-MeV α particles of ^{210}Po.[12] However, due to the smallness of pulse height, it was not possible to get the true time spectrum of signals without distortion. To observe the precise time spectrum of signals obscured by background noise, we developed a convenient measuring system consisting of commercially available instruments.[13] Besides, in the study of relaxation process of excited quasiparticles, we attempted to get analytically the radiation-induced signals by taking into account the recombination effect of quasiparticles.[14]

In the recent work,[15] we observed the pulse height distribution as well as the time spectrum of signals induced by a semiconductor pulse laser (300-nsec pulse width, 5 mW). However, due to rather poor heat exchange between the sample and the heat bath, it was difficult to deduce a reliable conclusion.

In the present work, we measured the time spectrum of electric signals induced by pulse laser light in an Sn-SnO_x-Sn superconducting tunnel junction (STJ). The STJ was biased with a constant current, and a $Ga_xAl_{1-x}As$ 15-nsec pulse laser was used as a source. Detailed experimental procedure and some discussion are presented.

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II. EXPERIMENTAL

A crossed-film Sn-SnO_x-Sn tunnel junction was prepared on a quartz substrate by means of the conventional vacuum evaporation of Sn (99.999%) and glow discharge oxidization. Evaporation speed was typically 15 Å/sec and total thickness was about 6000 Å. Seven samples out of 19 showed negative resistance at 300 K, but all became positive at 4.2 K.[16]

The STJ to be irradiated by laser light was mounted on a sample holder, and was immersed in a helium bath. Laser light was introduced onto the junction through a light fiber. Temperature was controlled by He evacuation and heater in the region of 1.37–4.2 K.

A calibrated Ge thermometer was used to measure sample temperature within uncertainty of 5 mK. The signal induced by laser light was measured by the so-called four probe method. Since the induced signal is so small, less than 10 μV, it is eventually obscured in the background noise.

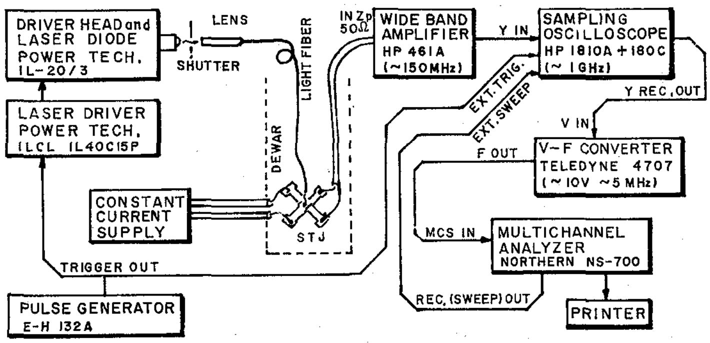

Fig. 1. Block diagram of the pulse-shape measuring system.

There are two predominant sources of noise, random and systematic noise. To get the true signals, we developed the measuring device combining an amplifier, a sampling oscilloscope (SOS), a multichannel analyzer (MCA) operated in the MCS mode, and some other components (see Fig. 1). The function of the system is as followings: Induced signals from the STJ are fed to the input terminal of the SOS through the amplifier. Triggering of the SOS is made by the trigger output signal of the laser power supply. Synchronization of the sweep of SOS to the MCA was made by the sawtooth signal for channel advance. Thus the signal appeared on the cathode ray tube of the SOS in each sweep is taken out from the Y-axis output terminal, and accumulated in the MCA after conversion through the voltage-frequency converter.

In principle, the random noise can be smoothed out by accumulating a sufficiently large number of signals, while the systematic noise increases in proportion to the accumulation time. However, it can be removed by subtracting the signals without laser irradiation. More details of this measuring system is reported in Ref. 13.

Although the sample is immersed in a helium bath, the thermal effect by laser light should be involved. To see this effect, prior to the pulse laser experiment, we examined the current-voltage (I-V) characteristics under irradiation of the He-Ne continuous gas laser (5.5 mW). Normal resistance of the sample used for the thermal effect was 5 mΩ at 4.2 K and the dc Josephson current was 35 mA at 1.37 K. To suppress the dc Josephson current, magnetic field of 19 gauss was applied.

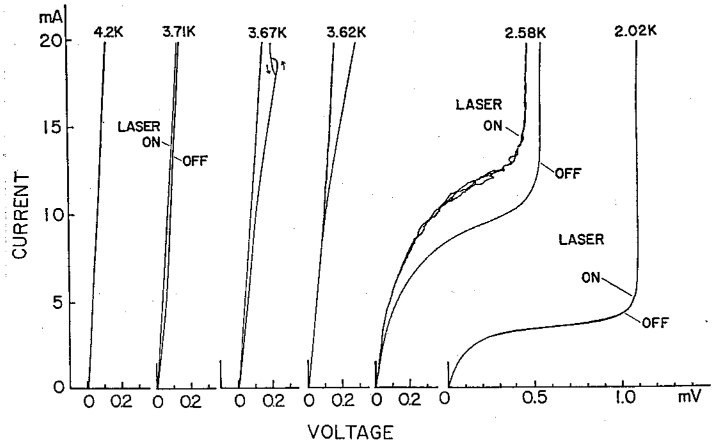

Fig. 2. The current-voltage curves of a superconducting tunnel junction with or without irradiation of a continuous laser light.

In Fig. 2 are shown some of the I-V curves of the junction at various temperatures. As seen in the figure, there is apparent difference in the response of I-V curves above and below $T_\lambda(=2.17\ \mathrm{K})$. This indicates that above T_λ, the heating effect is evident, but below that temperature laser on-off does not give rise to an appreciable change in the sample temperature. The instability appeared in the I-V curves just above T_λ is probably due to a convection current of liquid helium.

The pulse laser used in the present work is 15-nsec pulse width (bell shape), 20 W (peak power), and 7.4 kHz (repetition rate), which is equivalent to 2.22 mW of continuous laser light. Therefore, in the analysis of the laser-induced signals measured below T_λ, one may reasonably neglect the heating effect. Henceforth, the present experiment with pulse laser light was carried out at temperatures below T_λ.

III. RESULTS AND DISCIUSSION

Laser-induced signals were measured for 10 different bias currents at 1.37, 1.75, and 2.05 K. The STJ used has the normal resistance of 1 mΩ at 4.2 K. The dc Josephson current was 40 mA at 1.37 K, which was suppressed by 14 gauss dc magnetic field. In Fig. 3 are shown the points where measurements were carried out. In order to suppress the systematic noise, a set of two measurements was performed, where the current supply to the STJ was reversed in each measurement. This results in the complete cancel of direct electromagnetic pickup, because in this two measurements all impedances including the differential resistance of the STJ are identical.[7]

In Fig. 4 are shown thus observed time spectra, and some factors involved are

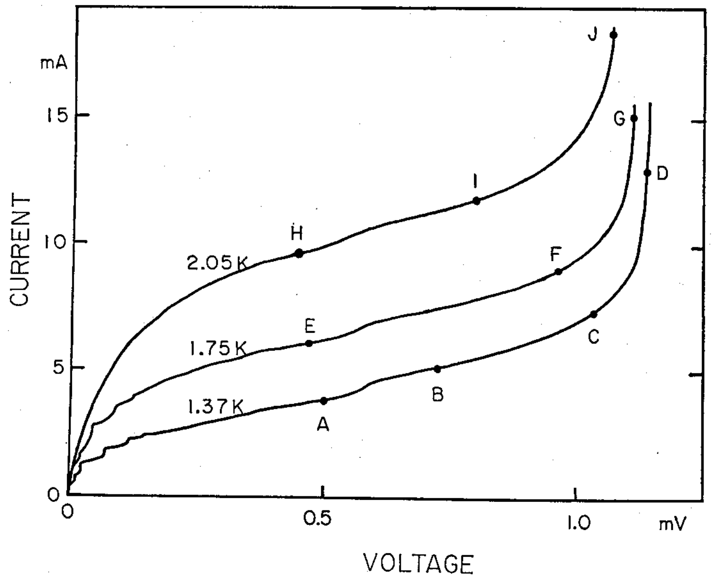

Fig. 3. Measuring points where the pulse laser experiment was carried out.

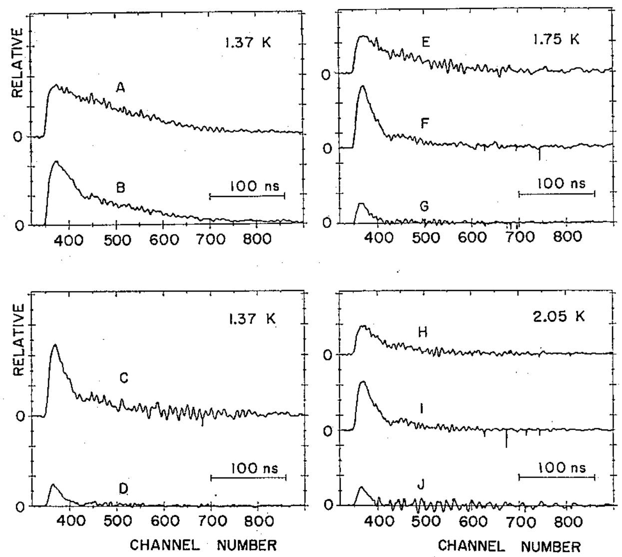

Fig. 4. Time spectra of laser-induced signals from a superconducting tunnel junction. Pulse heights are in arbitrary unit. A–J correspond to the points in Fig. 3.

listed in Table I. The spectra were confirmed to be laser-induced in the STJ by the following three reasons: First, the rise time of observed time spectra is 15 nsec, meaning that excess quasiparticles are accumulated during laser irradiation; second, the signals disappear when laser light is cut mechanically (not electronically); and third, as epxected no signals are observed at $T > T_c$, where T_c is the critical temperature of Sn, 3.72 K.

Table I. Specifications of the measurement of laser-induced signals, and some characteristic factors of the STJ. A–J correxpond to points in Fig. 3.

	T (K)	I_c (mA)	τ (nsec)	V_p (μV)	$\mathrm{d}V/\mathrm{d}I$ (Ω)	$I_c(\mathrm{d}V/\mathrm{d}I)$ (mV)	$C(\mathrm{d}V/\mathrm{d}I)$ (nsec)
A	1.37	3.8	102	510	0.294	1.117	1.47
B	〃	5.1	54.4	640	0.227	1.158	1.14
C	〃	7.4	24.6	700	0.072	0.533	0.36
D	〃	13.0	17.0	210	0.003	0.034	0.01
E	1.75	6.1	48.0	370	0.250	1.525	1.25
F	〃	9.1	20.4	610	0.095	0.865	0.48
G	〃	15.1	17.0	200	0.001	0.012	0.004
H	2.05	9.7	34.0	290	0.185	1.795	0.93
I	〃	11.8	19.5	480	0.152	0.794	0.76
J	〃	18.5	16.0	190	0.003	0.061	0.02

We can also say that the induced signals come surely from the non-equilibrium state, but not from the heating effect. This can be easily proved by comparing two time spectra above and below T_λ. If the heating effect plays an important role, the relaxation times of signals should differ considerably in these spectra, but the observed result was not the case.

From the spectra, we find the following facts.

(1) The relaxation time τ of signals, which is defined by assuming the simple exponential decay of signals, strongly depends on the bias current. Or, if we tentatively adopt the dynamic time constant of the STJ, $C\mathrm{d}V/\mathrm{d}I$, as a parameter, τ

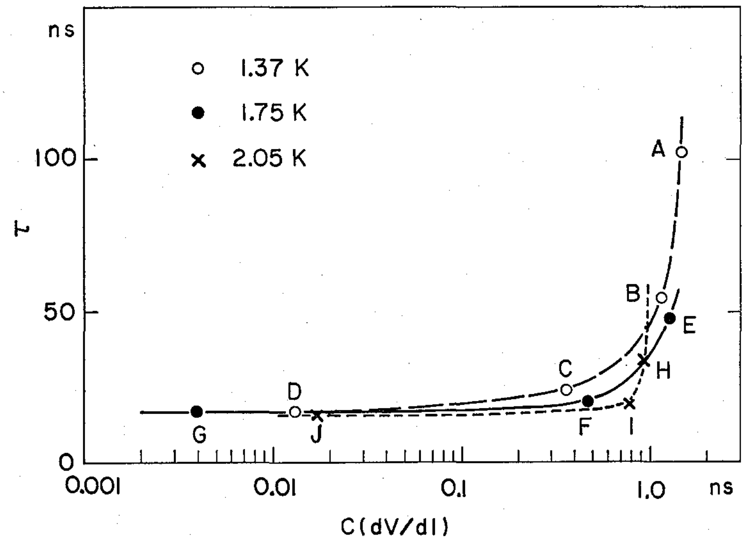

Fig. 5. The relaxation time τ of laser-induced signals versus the dynamic time constant $C\mathrm{d}V/\mathrm{d}I$ at each measuring point. A–J correspond to the points in Fig. 3.

decreases as the constant decreases, where C is the capacitance of STJ. But for $CdV/dI<0.1$ nsec, τ gives an asymptotic value of about 16 nsec, regardless of the experimental temperatures (see Fig. 5).
(b) The pulse height also depends on the bias current. At points D(1.37 K), G (1.75 K), and J(2.05 K), the pulse height reflects the change in the gap parameter Δ.
(c) In the spectra, a high frequency component is superimposed. By the fact that the mechanical shutter cannot remove it, this component is confirmed to come from the leakage radiation of pulse ringing generated in the laser driver. Besides, at around 450 channel of the spectra, there seems to be a small peak (see Fig. 4). Since the peak position shifts depending on the length of the coaxial cable used in the measuring system, the origin is considered to be electrical reflection. Test with a photodiode confirmed it. No further discussion will be given on (c).

Concerning (a), first we have to mention about the work by Hu *et al.*,[6] who used an Sn-SnO_x-Sn tunenl junction excited by 30-nsec argon-laser pulses and measured τ as a function of temperature. They reported that when biased at voltages less than the energy gap, τ effectively decreases as temperature goes up, and the value of τ is 30–100 nsec in the temperature range of 1.8–1.2 K. Since there is no concrete description on the bias voltage, it is not proper to compare with the present result. It seems therefore to be practical to examine if our asymptotic value of ($\sim$16 nsec) is reasonable for the present experimental layout. Unfortunately, to the authors' knowledge, no theoretical study has so far been published for such a strong perturbation as in the present case. Hence, rough discussion is given with an aid of the works for a weak perturbation (near thermal equilibrium).

In the previous work,[14] we derived analytically the relaxation time τ of the signals generated in an STJ by any weak perturbation. This is related to the effective recombination time of quasiparticles τ_{eff}, as well as to the current leak from the junction through measuring electrodes. Here, τ_{eff} is given by τ_r, the recombination lifetime of quasiparticles, multiplied by $(1+\tau_p/\tau_b)$, the phonon trapping factor, where τ_p is the phonon escape lifetime and τ_b is the meantime of phonon pair-breaking. And the current leak, being essential in this kind of measurement, means the fraction of excess quasiparticles which share in the constant bias current as electric current. The relation is approximately expressed by[14]

$$\frac{1}{\tau}=\frac{2}{\tau_{\mathrm{eff}}}+\frac{I_c}{eN_T}, \tag{1}$$

where I_c is the constant bias current. Note Eq. (1) is different from the equation in Ref. 14 by a factor of 1/2 in the second term. This is because laser light can produce excess quasiparticles only in one layer of the STJ. N_T, the number of thermally excited quasiparticles at temperature T, can be calculated by[12]

$$N_T=2N_0U\int_{\Delta_T}^{\infty}\frac{E}{(E^2-\Delta_T^2)^{1/2}}\cdot\frac{1}{\exp(E/k_BT)+1}dE, \tag{2}$$

where N_0 ($=2.12\times10^{22}\,\mathrm{cm^{-2}eV^{-1}}$ for Sn) is the density of states at the Fermi level for electrons of one spin orientation, U is the junction volume, k_B is the Boltzmann constant, and Δ_T is the gap parameter at T. N_T for the present case is 2.2×10^9 at 1.37 K, 7.9×10^9 at 1.75 K, and 20×10^9 at 2.05 K. Using N_T and the experimentally determined τ, τ_{eff} can be estimated through Eq. (1). For example, the values of τ_{eff} thus obtained are 25, 19, and 17 nsec for points D, G, and J, respectively.

In the meanwhile, according to Kaplan *et al.*,[17] who have made calculations of quasiparticle and phonon lifetimes in superconductors nearly in thermal equilibrium, the recombination lifetime τ_r of quasiparticles is expressed by

$$\frac{\tau_0}{\tau_r} \simeq \pi^{1/2}\left(\frac{2\Delta_0}{k_B T}\right)^{5/2}\left(\frac{T}{T_c}\right)^{1/2} \exp\left(-\Delta_0/k_B T\right), \tag{3}$$

where τ_0 is 2.30 nsec for Sn. Δ_0 is the gap parameter at $T=0$. Equation (3) gives $\tau_r=1.75$ nsec for Sn at $T=1.37$ K.

Rough estimation of τ_p can be given as the ratio of the phonon transit time across the sample to the phonon transmissibility at the interface. Thus, for the present sample, τ_p is in the order of nanoseconds. The meantime of phonon pair-breaking τ_b for Sn is in the order of 0.1 nsec at low reduced temperature ($T/T_c<0.4$).[17]

Adopting these values of τ_r, τ_p, and τ_b, one can find that τ_{eff} is several decades nanoseconds. This seems to be consitsent with the present experimental results.

It should be noted that as emphasized by Kaplan *et al.*, their theory is for quasiparticles and phonons in a dirty superconductor in or very near thermal equilibrium. As mentioned before, our previous work[14] is also in the frame of a weak perturbation. Therefore, direct comparison of the present data with these theories may not be attainable. However, importance is that the relaxation time of induced signals strongly depends on the bias current (or on the dynamic time constant of an STJ), and seems to have an asymptotic value.

Concerning (b), we analytically obtained the output signals from an STJ, where STJ is replaced by an equivalent circuit consisting of a diode and a capacitance.[14] According to this, the maximum pulse height of signals from the STJ can be approximately given by

$$V_p = I_c \frac{\mathrm{d}V}{\mathrm{d}I}\cdot\frac{N}{N_T}, \tag{4}$$

where N is the number of excess quasiparticles and N_T is the thermal population at T.

This analytical result shows that at the same temperature, V_p is proportional to I_c as well as to $\mathrm{d}V/\mathrm{d}I$. For different temperatures, however, the pulse height additionally depends on N/N_T. Unfortunately, the result is not properly reflected on the measurements (see Table I). One of the reasons of this discrepancy probably comes from the assumption adopted in the analysis, *i.e.*, the number of excess quasiparticles is much smaller than the thermal ($N/N_T\ll1$). As a matter of fact, at low reduced temperature (say $T/T_c<0.4$), the thermal population becomes extremely small and above assumption is not correct anymore.

In conclusion, we measured the time spectra of laser induced signals from an Sn-SnO$_x$-Sn superconducting tunnel junction at low reduced temperatures and at 10 different bias points. To avoid the heating effect, measurement at temperatures below $T_\lambda(=2.17$ K) is required. It has been revealed that the relaxation time of excess quasiparticles depends strongly on the bias current. This may be related to the dynamic time constant of the junction involved, although conclusive understandings on this parameter remain to be seen. The observed peak height cannot be explained by the weak perturbation analysis. Analysis for a strong perturbation is needed.

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REFERENCES

(1) D.H. Andrews, R.D. Fowler, and M.C. Williams, *Phys. Rev.*, **76**, 154 (1949).
(2) N.K. Sherman, *Phys. Rev. Lett.*, **8**, 438 (1962).
(3) D.E. Spiel, R.W. Boom, and E.C. Crittenden, Jr., *Appl. Phys. Lett.*, **7**, 292 (1965).
(4) G.H. Wood and B.L. White, *Appl. Phys. Lett.*, **15**, 237 (1969).
(5) L.R. Testardi, *Phys. Rev. B*, **4**, 2189 (1971).
(6) P. Hu, R.C. Dynes, and V. Narayanamurti, *Phys. Rev. B*, **10**, 2786 (1974).
(7) I. Schuller and K.E. Gray, *Phys. Rev. Lett.*, **36**, 429 (1976).
(8) C.C. Chi and D.N. Langenberg, *Bull. Am. Phys. Soc.*, **21**, 403 (1976).
(9) P. Hu, R.C. Dynes, V. Narayanamurti, and W.F. Brinkman, *Phys. Rev. Lett.*, **38**, 361 (1976); V. Narayanamurti, R.C. Dynes, P. Hu, H. Smith, and W.F. Brinkman, *Phys. Rev. B*, **18**, 6041 (1978).
(10) R. Buisson, R. Chicault, F. Madeore, and R. Romestain, *J. Phys. Lett.*, **39**, L130 (1978).
(11) A.I. Golovashkin, O.M. Ivanenko, K.V. Mitsen, G.P. Motulevich, and A.A. Shufin, *Zh. Eksp. Teor. Fiz.*, **75**, 1517 (1978) [*Sov. Phys. JETP*, **48**, 766 (1978)].
(12) M. Kurakado and H. Mazaki, *Phys. Rev. B*, **22**, 168 (1980).
(13) M. Kurakado, R. Katano, and H. Mazaki, *Nucl. Instr. Methods*, **198**, 321 (1982).
(14) M. Kurakado and H. Mazaki, *Nucl. Instr. Methods*, **185**, 149 (1981).
(15) M. Kurakado, S. Tachi, R. Katano, and H. Mazaki, *Bull. Inst. Chem. Res., Kyoto Univ.*, **59**, 106 (1981).
(16) M. Kubota, K. Kanoda, and H. Mazaki, *Bull. Inst. Chem. Res., Kyoto Univ.*, **62**, 233 (1984).
(17) S.B. Kaplan, C.C. Chi, D.N. Langenberg, J.J. Chang, S. Jafarey, and D.J. Scalapino, *Phys. Rev. B*, **14**, 4854 (1976).